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BED MATERIAL ANALYSIS ON THE FALL RIVER

WRFSL Project Report No. 83-6P

Submitted:

As Fulfillment of the Requirements

for CE 695C

Independent Study - Hydrology

Dr. Colin R. Thorne, Advisor

by

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I. INTRODUCTION

The Fall River flows eastward from the Continental Divide a distance of about 22.5 km to its confluence with the Big Thompson River near Estes Park, Colorado (Figure 1). In the upper reaches the Fall River is a very steep mountain stream with a coarse cobble and boulder bed. In the vicinity of Horseshoe Park, the river enters a wide glacier-carved valley where it develops an extremely sinuous pattern. Through this area the streambed is predominately sand and fine gravel. Downstream of Horseshoe Park the channel gradient increases again and the streambed is composed of coarse gravel and cobbles.

The Roaring River flows southward out of Lawn Lake a distance of about 7 km to its confluence with the Fall River in Horseshoe Park. The Roaring River is predominately a coarse cobble and boulder bed stream with a steep slope of approximately 10%. Lawn Lake Dam was an earthen dam constructed on the Roaring River between 1903 and 1914 and it controlled approximately three square miles of the Roaring River drainage basin. The storage capacity of Lawn Lake was approximately 820 acre-feet. On the morning of July 15, 1982, with Lawn Lake filled to capacity, the dam failed. Over 800 acre-feet of water was released down the Roaring River, uprooting trees and scouring the channel to bedrock. As the flow exited the steep canyon of the Roaring River and encountered the relatively mild slope (0.5%) of the Fall

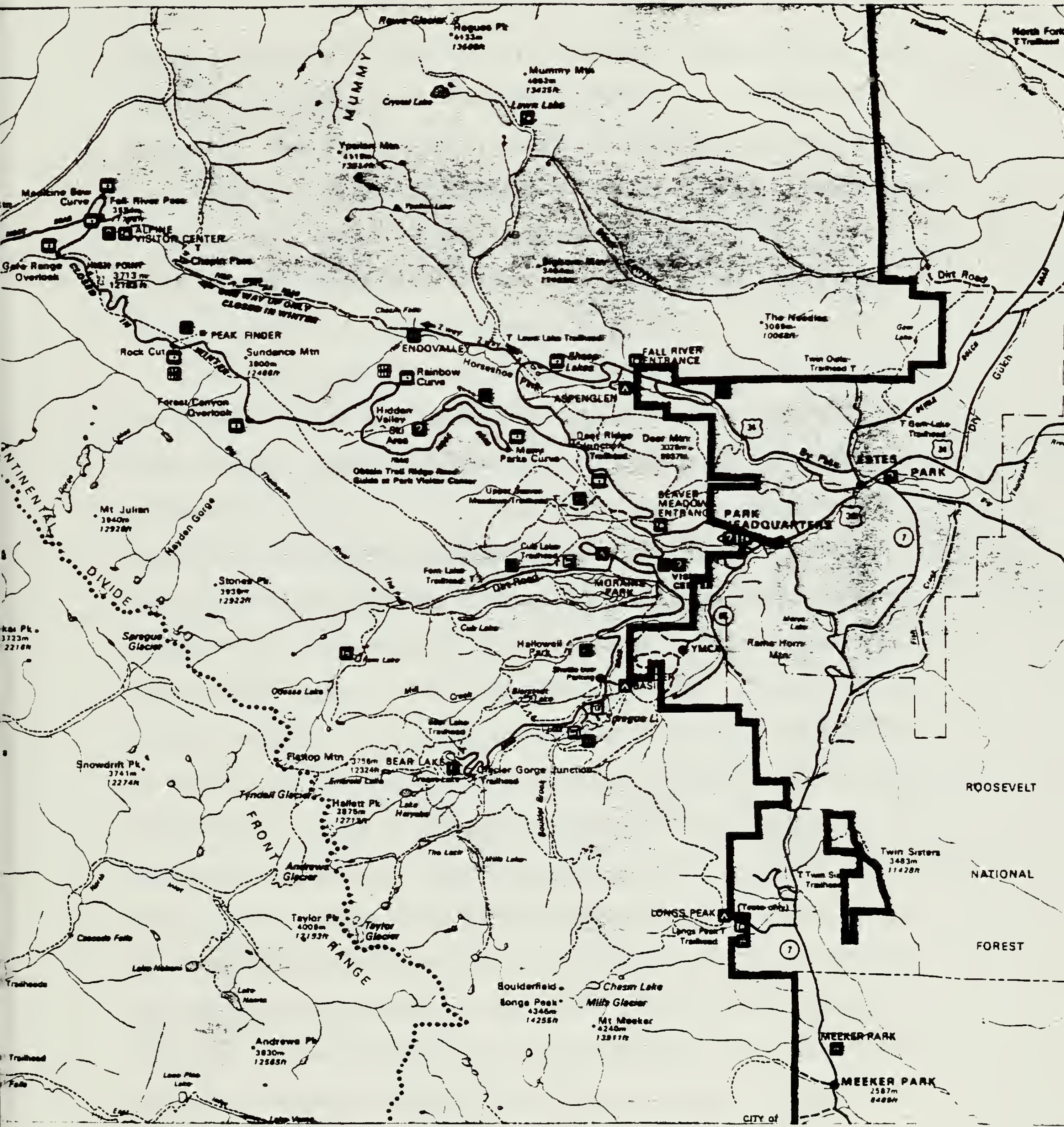

Figure 1. Fall River Vicinity Map

River, a large alluvial fan was formed. This alluvial fan consists of debris and boulders as large as 10 meters in diameter. The flood waters eventually passed through Estes Park causing millons of dollars worth of damage. Downstream of Estes Park the flow was contained by the Bureau of Reclamation's regulating reservoir, Lake Estes, preventing further damage in the Big Thompson Canyon.

The first period of high flows since the dam failure occurred with the spring snowmelt starting in May 1983. Prior to this maximum flows were only about 0.9m^3/s and morphologic changes in the Fall River were insignificant. During the spring and summer the channel began to respond to the higher flows due to the snowmelt. Large quantities of sediment that had been stored in the valley following the dam failure began to be flushed downstream. The deposition of this sediment in the populated areas further downstream on the Fall River poses potential problems with water quality, flooding, and loss of reservoir capacity at Lake Estes. An understanding of the channel response on the Fall River below the alluvial fan provides an excellent tool for predicting the extent of future problems downstream. Personnel from Colorado State University have been studying the channel response by analyzing cross sectional data, plan and profile changes, sediment transport, and bed material variations. This report reflects only a small portion of this on-going study. The purpose of this report is to document the armoring process in the upper 240 meters of the Fall River

downstream of the alluvial fan.

II. FIELD STUDY

A. Description of Study Reach

A sketch of the study area is shown in Figure 2. The lake shown in this figure was formed by the alluvial fan at the confluence of the Fall River and the Roaring River. The distance between the lake and the downstream limits of the study area is approximately 240 meters. Five reaches were selected for bed sampling (Figure 2). In this report Reaches 2 and 4 will be referred to as the upper reaches and Reaches 6, 9, and 11 will be referred to as the lower reaches.

The study reach has two sources of water and sediment input. The Fall River flows out of the lake into the upper end of the reach with essentially a sediment-free discharge. The Roaring River wanders across the alluvial fan through numerous channels. These channels are very unstable and their locations change on a daily basis. At times the Roaring River has a considerable sediment load. Most of this sediment is transported from the alluvial fan; however, the caving banks in the upper Roaring River canyon periodically produce a significant sediment load.

B. Variations in Plan and Profile

Changes in plan and profile in the study reach are

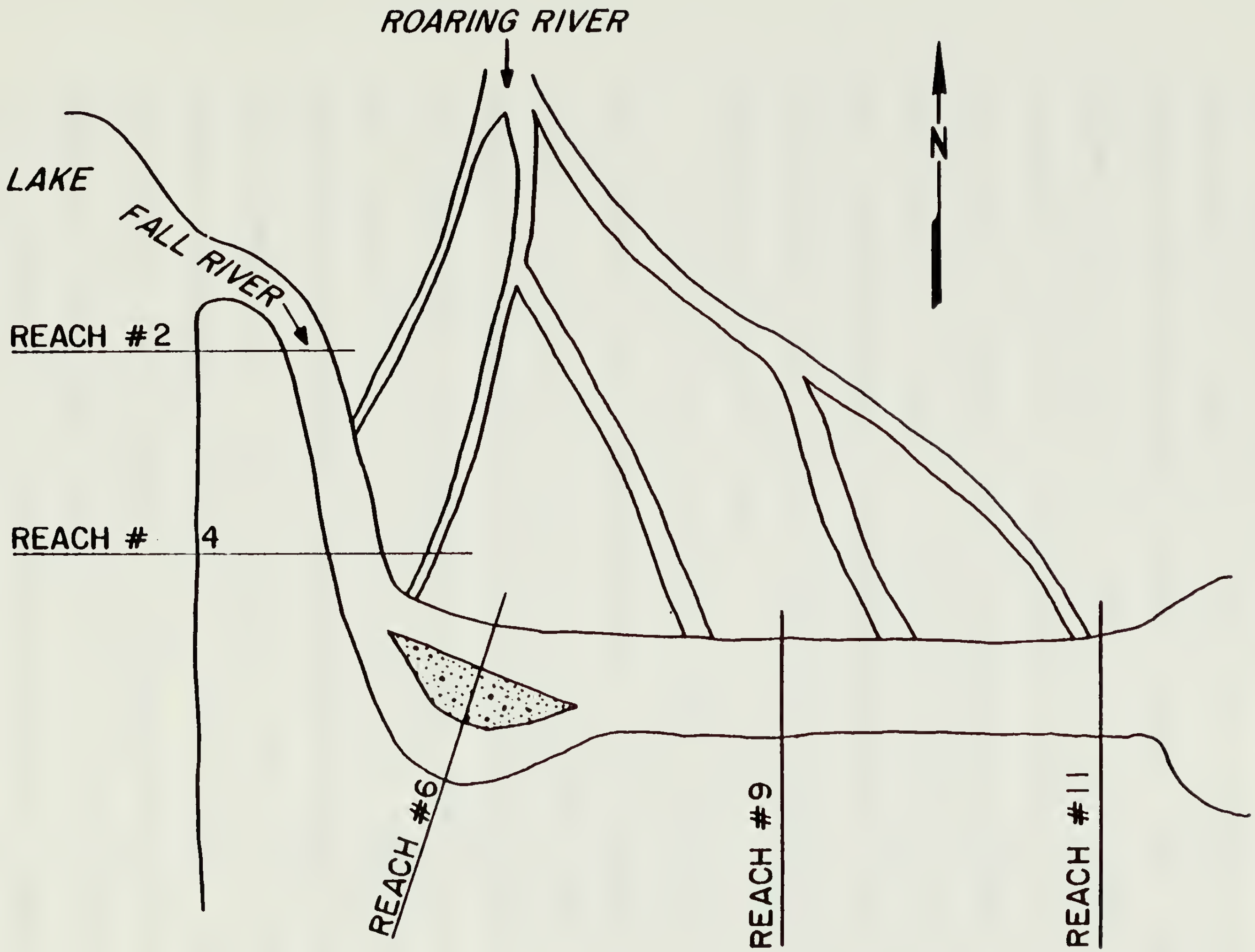

Figure 2. Fall River Study Reach Location Map

directly related to changes in discharge. Prior to June 10, 1983, the discharges in the channel were relatively low, ranging from about $2.3m^3/s$ to $4.3m^3/s$. During this period the channel was relatively stable with an average width and depth of about 6m and 0.2m, respectively. Thalweg slopes varied from about 2% in the upper reaches to about 0.65% in the lower reaches (Figure 3). The main flow from the Roaring River intersected the Fall River in the vicinity of Reach 4 (Figure 2). There were some small distributaries of the Roaring River cutting across the alluvial fan; however, these were only minor channels carrying very little flow.

On the evening of June 10, 1983, the first major flow event of the summer occurred. A discharge of $6.6m^3/s$ was measured the next day; however, the discharge on the previous evening was probably much greater since the peak flows generally occur late in the evening. As a result of the increased discharges, the Roaring River developed numerous distributary channels across the alluvial fan. These channels deposited large quantities of sediment in the Fall River channel. The aggradation of the channel is illustrated by the comparison of the June 10 and June 12 thalweg profiles shown in Figure 4. According to Figure 4, approximately 0.4m to 0.8m of aggradation occurred in the upstream channel. This aggradation extended downstream to a point about 16m upstream of Reach 9. Downstream of

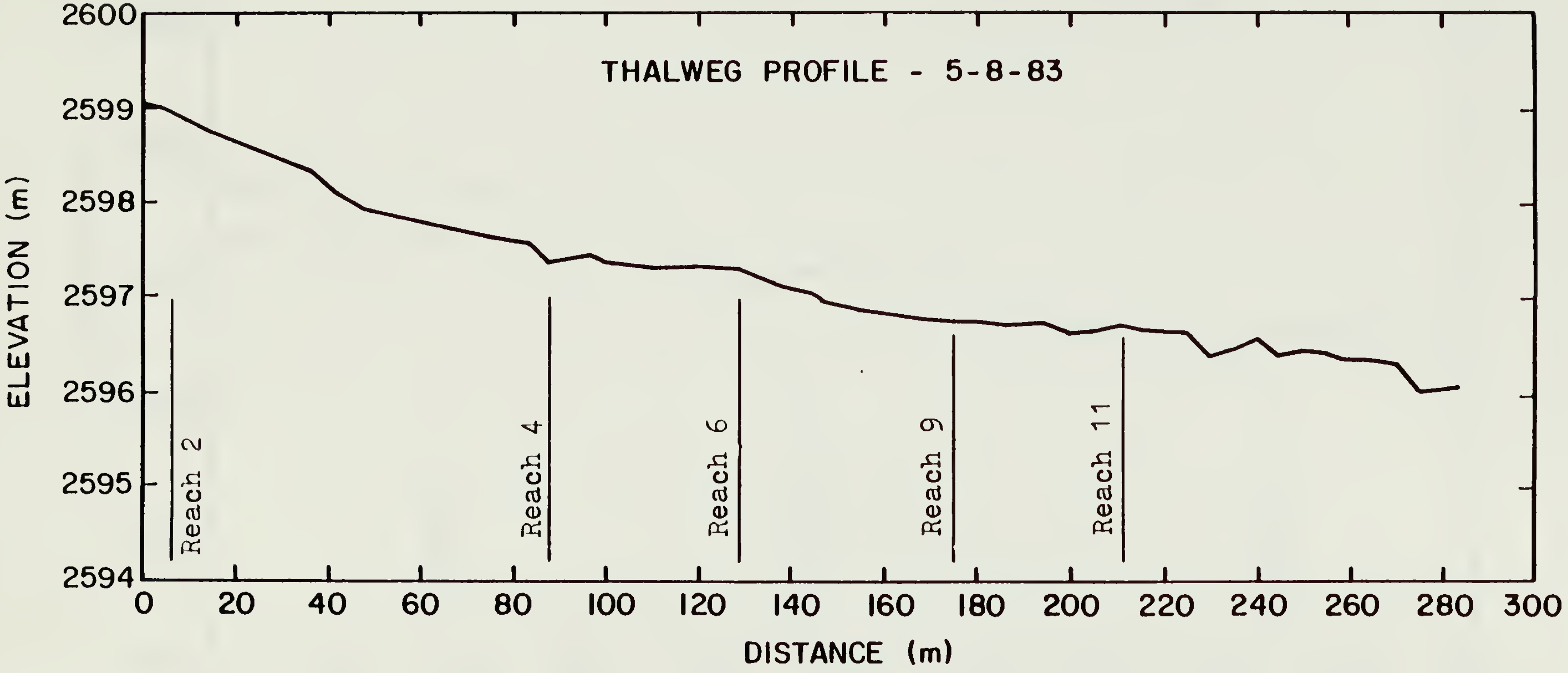

Figure 3. Fall River Thalweg Profile - 5-8-83

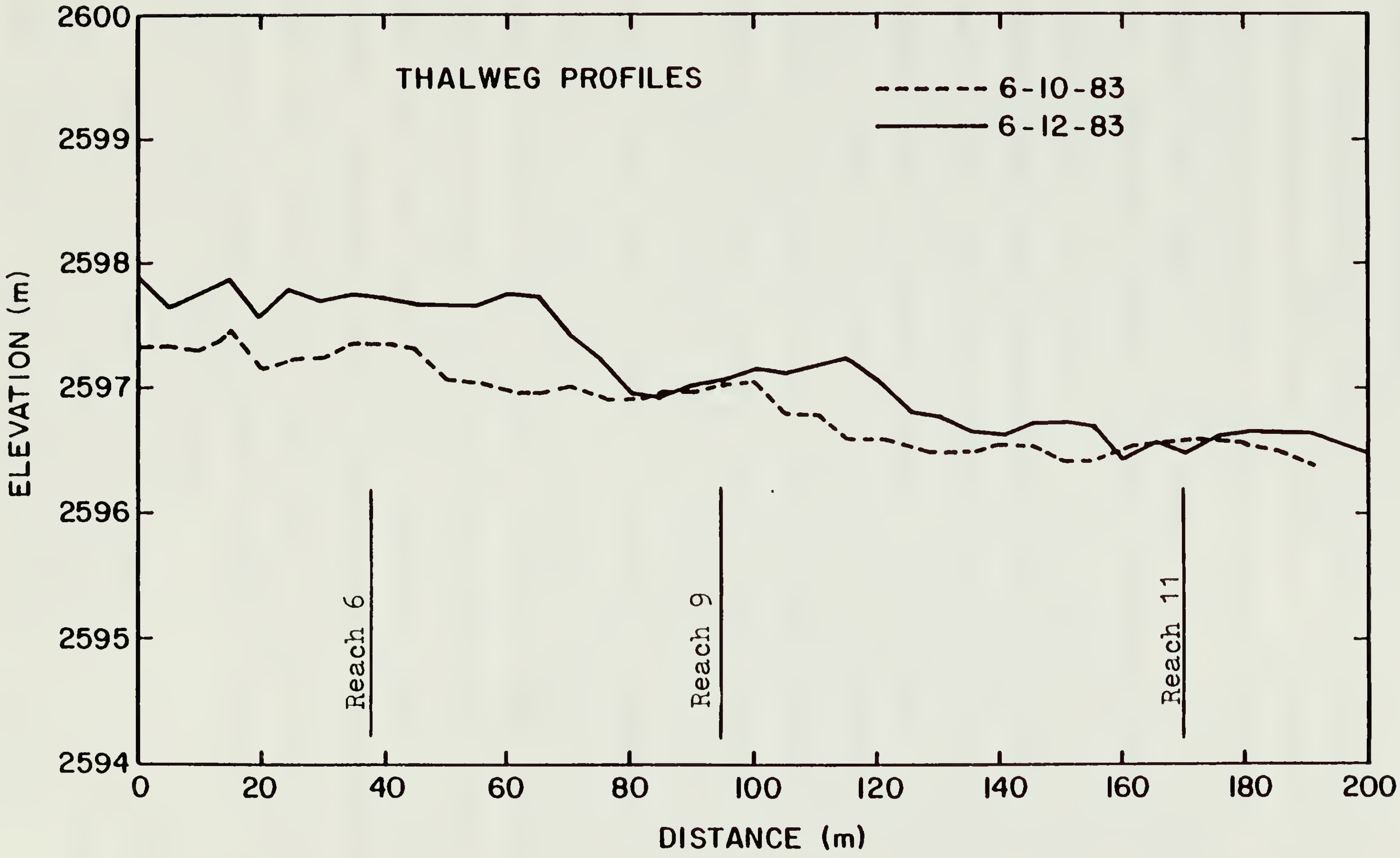

Figure 4. Fall River Comparative Thalweg Profiles - 6-10-83 and 6-12-83

Reach 9 there was some filling of the channel, but it was much less noticeable.

During the period June 10 to July 15, discharges varied between 6.2m^3/s and 10.6m^3/s. As a result of the continued high flows the channel remained unstable. The Roaring River began to shift downstream until the main flow intersected the Fall River at several locations between Reach 6 and Reach 11. As a result of the increased water and sediment input into this area, the lower reaches were very unstable and at some locations tended toward a braided pattern. The shifting of the Roaring River across the alluvial fan significantly reduced the sediment input into the upper reaches. Consequently these reaches were much more stable.

Sediment transport during this period (June 10 - July 15) was highly variable. Generally the channel bed consisted of coarse gravel and cobbles with a small bed load of sand and small gravel. However, during certain periods the channel would fill with sand and a very mobile bed would result. The increased velocities and sediment transport were the result of the reduced roughness under the sand bed conditions. During these periods it was not uncommon to observe cobbles as large as 150mm moving over the mobile sand bed.

After July 15 the flows decreased to about 4.3m^3/s. Concurrent with the reduced discharges, the lower reaches began to adjust back to their approximate original

location. With the reduced sediment input in this area it appeared that the channel was attempting to armor. In the upper reaches the armor development was much more noticeable.

C. Bed Material Sampling

Bed material was analyzed using the grid-by-number method devised by Wolman (1954) at six different reaches shown in Figure 2 during the period from May 24, 1983 to July 19, 1983. Samples were collected on seven occasions. Kellerhals and Bray (1971) suggested the grid-by-number sampling procedure for sampling surface material in gravel bed streams principally because of its theoretical equivalence with bulk sieve analysis. The grid network over each reach was established by pacing, and the stones were selected by picking up the stone first touched by the finger next to the tip of the toe of the boot, with eyes averted or closed. At each reach a sample size of about 100 stones was collected and the intermediate diameter of each sampled stone was measured with a specially constructed gravelometer (Hey and Thorne, 1983). Effectively, this procedure produces similar results as sieving and eliminates operator error due to estimation of the intermediate diameter using a ruler or a pair of calipers. It should be noted that the intermediate diameters measured with the gravelometer will systematically produce smaller diameters than those measured with ruler or calipers,

since the stone can pass diagonally through the hole. After measurement, the stone was tossed onto top bank to avoid the possibility of sampling the same stone more than once.

III. DATA ANALYSIS

A. Size Distributions

The bed material was analyzed by the number, rather than the weight of stones in a particular size range. The size distribution curves shown in Figures 5-9 were developed based on the number of stones in each ϕ class:

$$\phi = -\log_2 D$$

where D is the particle diameter in millimeters. These curves reflect the variations in the bed material size during May, June, and July 1983. The variations in D_{50} through the study reach during this same time period are shown in Figure 10.

B. Bed Material Analysis

Figure 10 shows that considerable variation in D_{50} existed along the channel in the initial condition (May 24). The reduction in D_{50} downstream of Reach 2 is due to the fine sediment input from the Roaring River which at that time confluenced with the Fall River just upstream of Reach 4. Further downstream the bed was coarser, particularly at Reach 11. The coarseness of

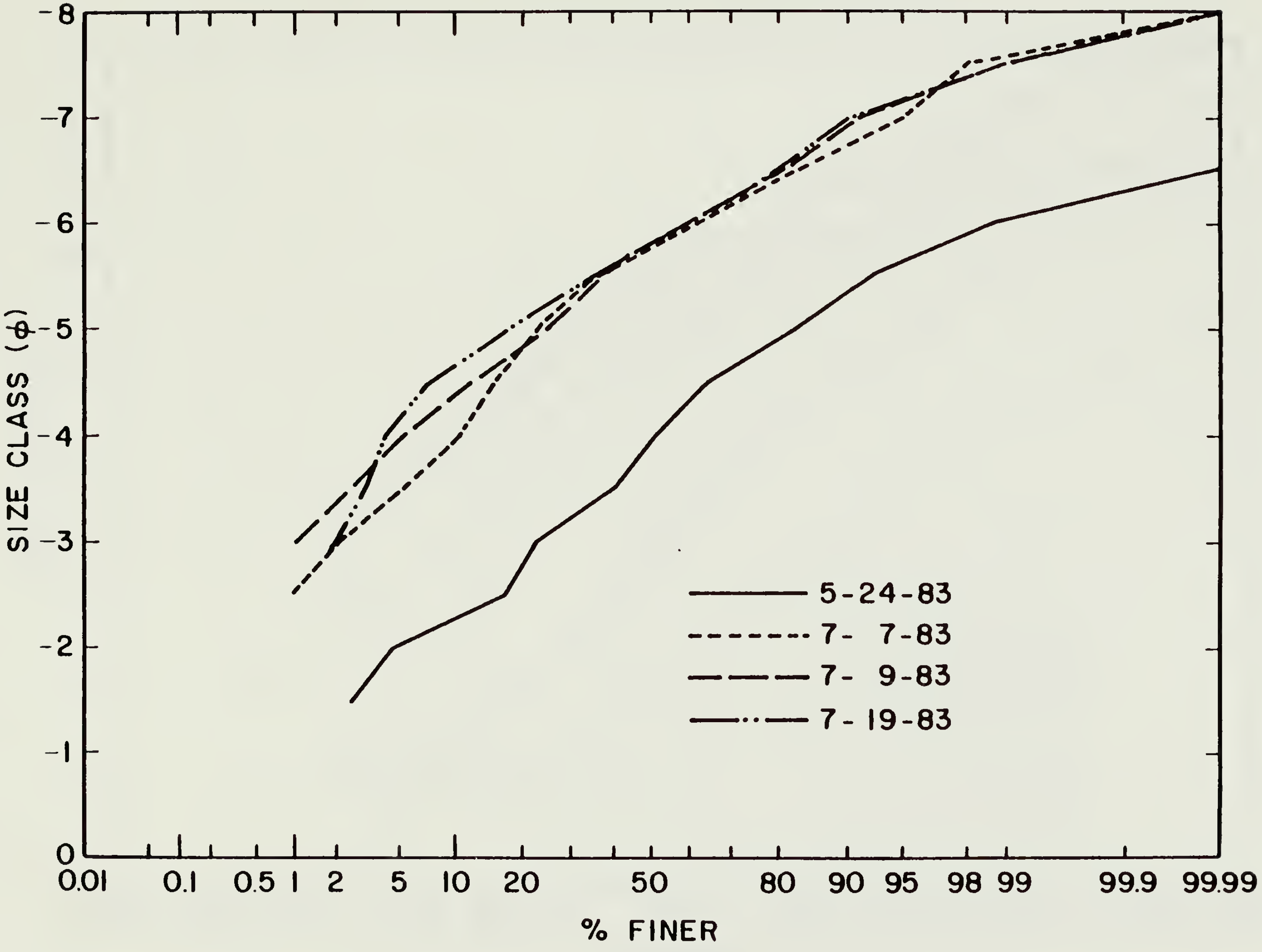

Figure 5. Size Distribution Curve - Reach 2

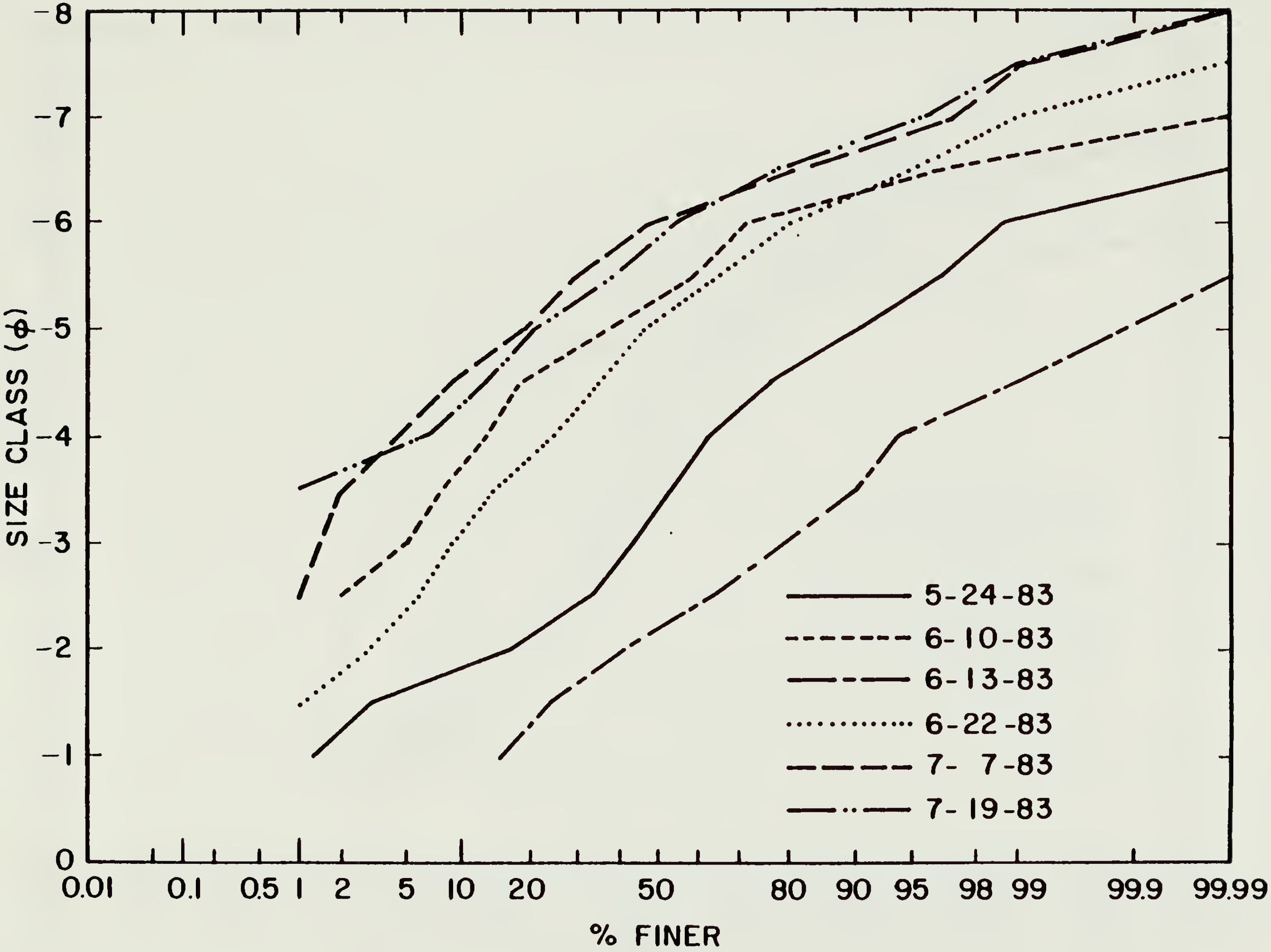

Figure 6. Size Distribution Curve - Reach 4

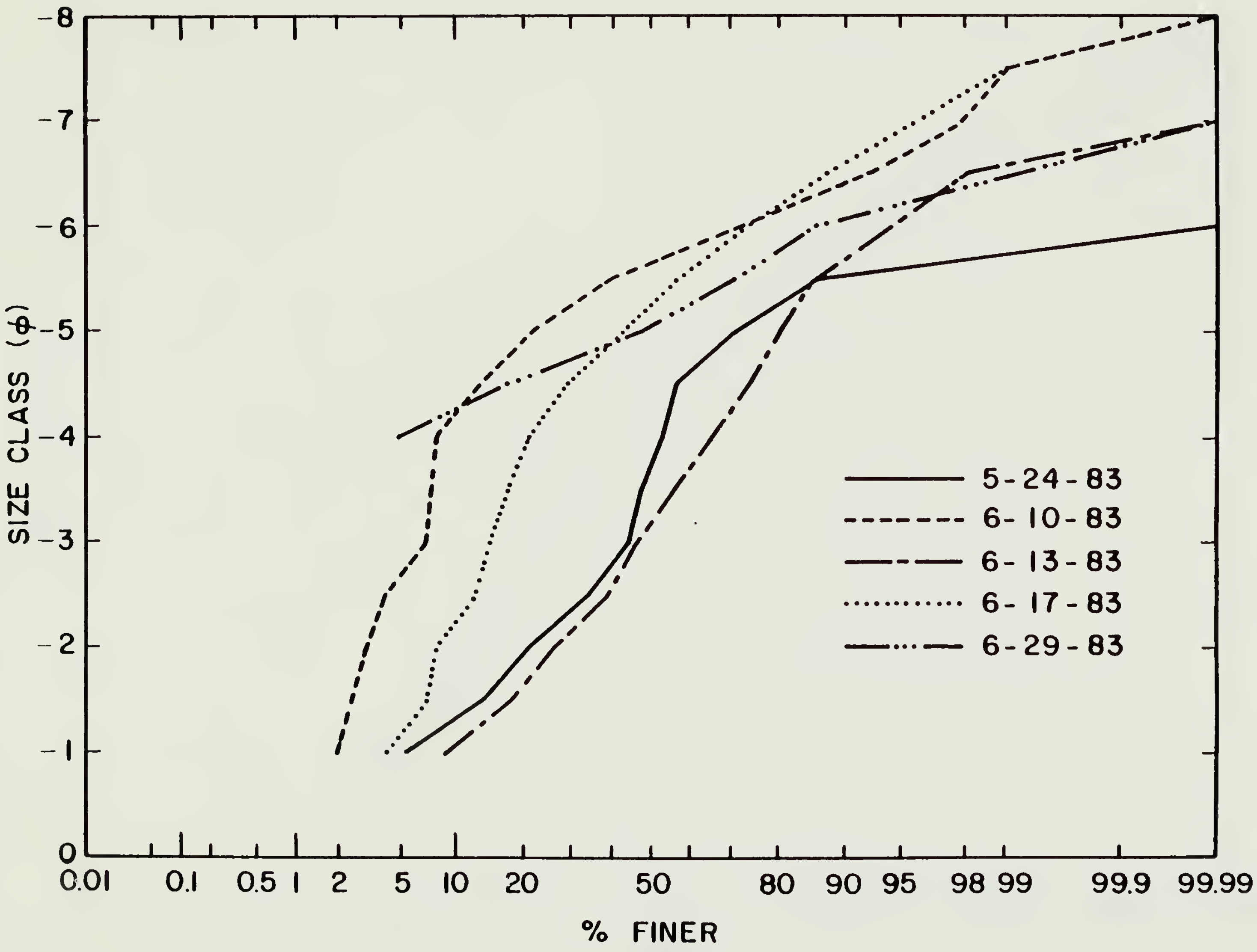

Figure 7. Size Distribution Curve - Reach 6

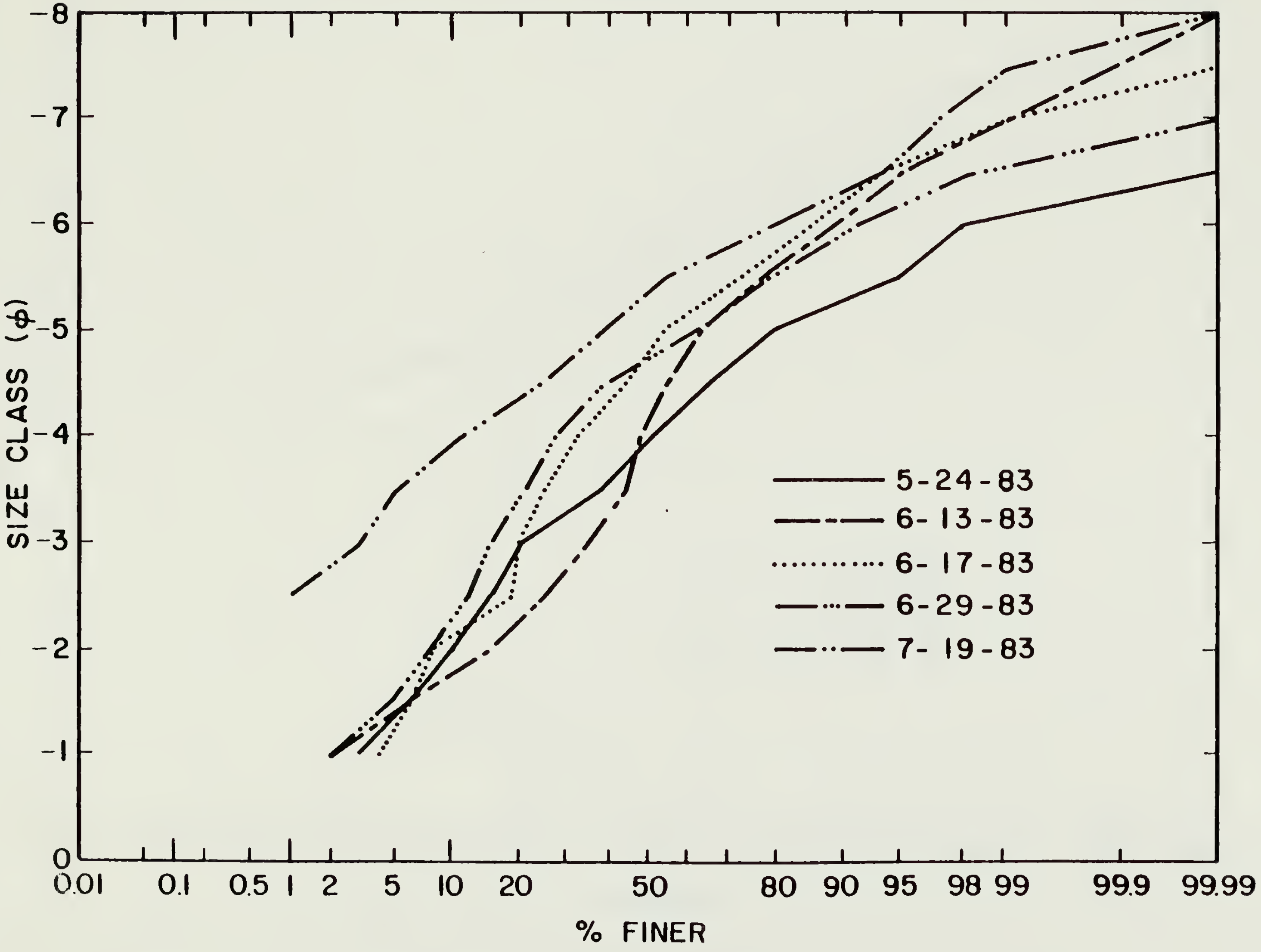

Figure 8. Size Distribution Curve - Reach 9

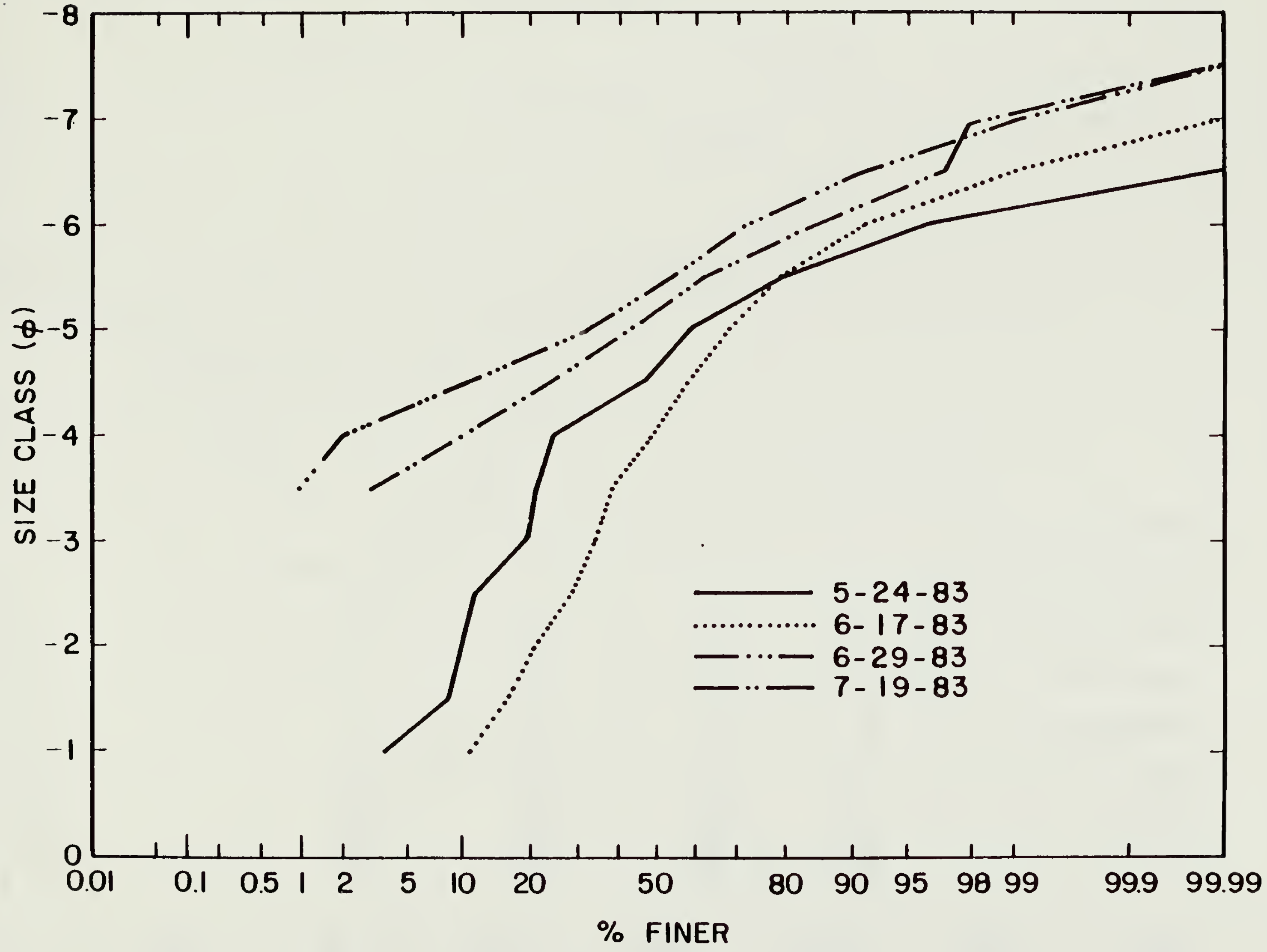

Figure 9. Size Distribution Curve - Reach 11

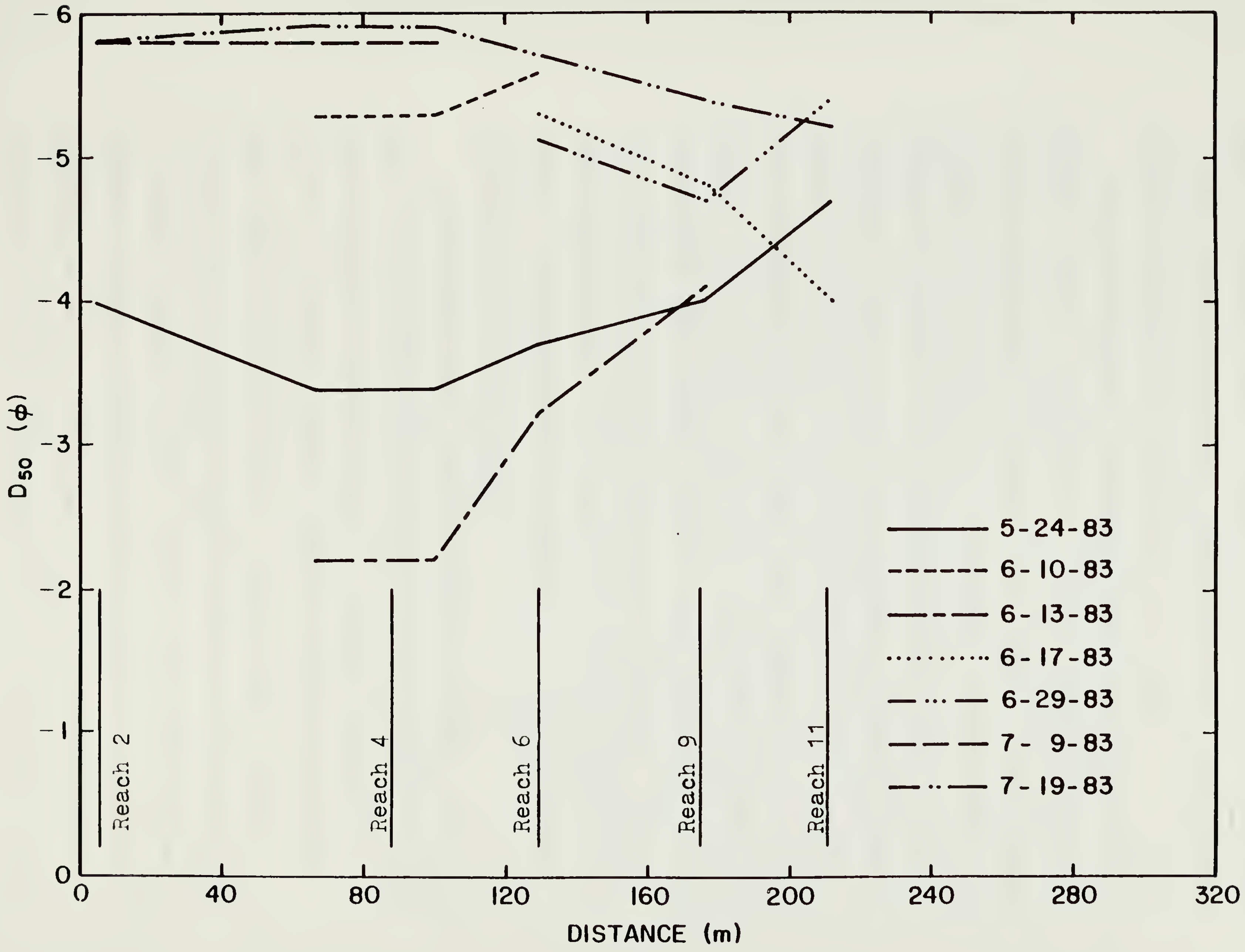

Figure 10. Variation in D_{50}

Reach 11 is difficult to explain; however, it is probably a result of the deposition pattern of coarse material in the fan following the dam break last summer.

The bed material was sampled again on June 10 at Reaches 4 and 6. Figures 6, 7 and 10 indicate that the bed was coarsening. However, this trend was drastically changed that evening as the discharge increased and the channel was filled with tremendous quantities of fine sediment. The effects of the sediment input were most dramatic at Reaches 4 and 6, where the channels were almost completely filled with sand (Figures 6, 7 and 10). Figures 8 and 10 show that Reach 9 was not significantly affected by the sediment input, which indicates that the sand fill did not extend that far downstream. Field investigations and the comparative thalweg profiles in Figure 4 confirm that the channel fill did not extend downstream as far as Reach 9.

The channel fill did not persist for very long. By June 17 the channel had flushed out the majority of the sand and the bed again began to coarsen (Figures 7, 8 and 10). However, Figures 9 and 10 indicate that at this time the bed at Reach 11 became finer. Reach 11 is at the head of a large braided reach and was developing a somewhat braided pattern itself. This reach acts as a natural sediment storage area. As the fine material was transported out of the upper reaches it was deposited in the braided reach, explaining why the bed became finer

at Reach 11.

As the Roaring River continued to shift further downstream on the alluvial fan the upper reaches began to coarsen. The lower reaches also continued to coarsen, but to a lesser extent due to the continued input of sediment from the Roaring River. Once the flows began to decrease, after July 15, Reaches 9 and 11 shifted back to approximately their original locations. The original channel at Reach 6 was not discernible due to the large input of several large Roaring River distributaries in this area. On July 19 all reaches (except Reach 6) were sampled one last time. Figure 10 indicates that the upper reaches had developed a much coarser bed than the lower reaches. Since the peak snowmelt period is over and the flows are getting progressively smaller, the bed should not coarsen any further. Therefore, the July 19 data reflects the final development of the armor layer this year.

The gradation curves (Figures 5-9) indicate that the channel bed did tend to armor. However, it appears that two different armoring processes occurred. The upper reaches have practically no sediment input and they remained relatively stable throughout the snowmelt. The armoring that has occurred in these reaches is similar to that downstream of a dam with a clear water release. In this case the armor layer is formed as the fine material is transported out leaving behind a coarse

bed layer. Bray and Church (1980) defined this process, which results eventually in an immobile bed, as "paving". During July it was noted that the bed in the upper reach was becoming more and more imbricated so that even the smaller particles were extremely difficult to remove from the bed. Additionally there was a build-up of approximately 10mm of slimy algal growth on the channel bed. Both the imbrication and the algal growth are indications of an immobile bed with very little sediment input. Therefore, according to Bray and Church's definition this upper reach developed a pavement. The bed will remain immobile until a flow large enough to break up the pavement occurs; however, since this pavement was formed by flows from a very large snowmelt, it may take years before an event large enough to destroy the pavement occurs.

The armoring process in the lower reaches was much more complicated than that in the upper reaches due to the sediment input of the Roaring River. The unstable nature of this reach made it difficult to sample the bed consistently because of channel shifting. Consequently comments on changes in this reach are more tentative. Although the bed did coarsen up after mid-July, the gravel in the bed was still very loose and not well imbricated. Also, there was no evidence of algal growth. This indicates that the coarsening produced a mobile bed. Bray and Church (1980) defined

this process, on a mobile bed, as "armoring".

Procedures have been developed for predicting the the size distribution of the armor layer on the basis of the parent material and the flow hydraulics. Application of these methods to predict the armor layer on the Fall River is difficult however, due to the extremely dynamic behavior of this system. Still, two procedures were used to try and predict the size distribution of the armor layer, and the results were compared to the actual size distributions.

The procedure presented by Little and Mayer (1976) was the first method used to predict the armor layer. This procedure is based on a flume study of log normally distributed sand with a geometric mean diameter of 1.00mm. The results of this method indicated that the channel bed would not armor. The development of the armor coat in the channel indicates that this method is inapplicable to highly dynamic, coarse gravel streams with considerable sediment input. This is not surprising considering that this procedure was developed for sand sizes in a flume study.

Gessler (1970) presented the following equation of the grain size distribution of the armor layer:

$$P_a(d) = \frac{\int_{d_{min}}^{d} qP_o(d)dd}{\int_{d_{min}}^{d_{max}} qP_o(d)dd}$$

where $P_a(d)$ is the probability distribution function of the armor layer, $P_o(d)$ is the probability density function of the grain size distribution, and q is the probability that a particular grain size d will not be removed. Then

$$q = f\,(\tau_c/\bar{\tau})$$

where τ_c is the critical shear stress for a particular grain size d, and $\bar{\tau}$ is the average bed shear stress. Komura (1971) proposed the following finite form of Gessler's equation:

$$P_a(d) = \frac{\sum_{d_{min}}^{d} q(d)\,P_o(d)}{\sum_{d_{min}}^{d_{max}} q(d)\,P_o(d)}$$

The computational procedure for the above equation presented by Simons and Senturk (1977) was used to predict the size distribution of the armor layer on the Fall River. A comparison of the predicted D_{50} of the armor layer and the observed D_{50} is presented in Table 1. The results indicate a fairly close agreement between predicted and observed values of D_{50} in the upper reaches, while the lower reaches show a large discrepancy. This is understandable considering that the upper reaches are relatively stable and have essentially no sediment input; therefore they more closely reflect flume conditions than

do the unstable lower reaches. The large difference between the observed and the predicted values of D_{50} in the lower reaches is due to the sediment input from the Roaring River distributaries and the extreme lateral instability of the channel. In all instances the observed D_{50} was less than the predicted D_{50} in the lower reaches due to the input of fine sediment from the alluvial fan.

Table 1. Comparison of Predicted and Observed Values of D_{50}

Reach	D_{50_A} (Predicted) (mm)	D_{50} (Observed) (mm)	% Diff. $(D_{50_A} - D_{50})/D_{50}$
2	67	56 (7-19-83)	19%
4	55	59.7 (7-19-83)	-8%
6	45	33.1 (6-29-83)	36%
9	55	42.2 (7-19-83)	30%
11	55	36.8 (7-19-83)	49%

IV. SUMMARY

The channel response on the Fall River downstream of the alluvial fan provided an excellent opportunity to observe the armoring process on a highly disturbed channel. Armoring has generally been studied under less dynamic conditions such as downstream of a dam or in laboratory flumes. The armoring process can be extremely complicated if the channel is

laterally unstable and has a significant sediment input, as was the case on the lower reaches of Fall River.

At the beginning of this summer the bed gradation curves on the Fall River reflected a wide variation in sediment sizes, ranging from fine sands to cobbles as deposited by the flood. As the flows increased due to the snowmelt the finer particles were flushed out leaving behind a coarse layer. This trend toward an armor layer was interrupted intermittently by large inputs of sediment. Once this fine sediment was removed the channel would begin to coarsen once again. This situation was further complicated by the continual lateral shifting of certain reaches of the channel. With time the Roaring River shifted downstream leaving the upper reaches essentially free of any sediment input. Consequently the armoring process for the upper and lower reaches was entirely different. The upper reach developed a very coarse ($D_{50} \approx 58$mm) well imbricated, immobile bed, which is similar to the development of a pavement downstream of a dam with a clear water release. The lower reaches formed an armor layer on a mobile bed that was not as coarse ($D_{50} \approx 37$mm) or as well imbricated as the upper reaches. The development of an armor layer by two different processes is noteworthy, especially considering the short length (240m) of this reach.

Two procedures were used to predict the size distribution of the armor coat. The procedure presented by Little and Mayer (1976) was not considered applicable to this stream since it was based on flume studies of fine sands.

The computational procedure presented by Simons and Senturk (1977) for predicting the armored size distribution using Gessler's equation gave better results. This procedure gave better results for the upper reaches than for the lower reaches. This is explained by noting that the upper reaches were relatively stable and had essentially no sediment input; therefore they more closely reflected flume conditions used to develop the equation than did the lower reaches.

The peak of the snowmelt period ended in mid-July. With the reduction in flows the channel became more stable. Therefore it appears that channel changes will only be significantly active during a few months each summer concurrent with the peak snowmelt period. Consequently it may take this channel many years to reach a state of relative equilibrium. During this period of adjustment it would be worthwhile to document the continued variations in the armoring process. Because of the highly variable nature of the Roaring River as it wanders across the alluvial fan, it is possible that the armoring trends noted this past summer may be completely different in years to come. The highly dynamic behavior of this system warrants further studies on the armoring processes for the next several years.

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